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Role of transfer reactions in heavy ion fusion : a detailed experimental investigation

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Abstract : Transfer probabilities in one- and two-nucleon transfer reactions were studied as function of the distance of closest approach in $^{32}S + ^{64}Ni$ and $^{28}Si + ^{68}Zn$ systems at various energies near the Coulomb barrier. The coupling strengths, derived from the data using a semiclassical theory, were used to calculate fusion cross sections and average angular momenta The calculated values agree reasonably well with the existing fusion data in the two systems.

Keywords : Transfer reactions, heavy ion fusion

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Investigations of the rich variety of phenomena that occurs in heavy ion collisions near the Coulomb barrier have received a lot of attention in recent years [1]. A great deal of advances has been made in understanding the dynamical aspects of the heavy ion direct reactions, such as inelastic excitation and a few nucleon transfer, by the semiclassical theories [2,3]. On the other hand, a clearer picture of evolution of the heavy ion collisions leading to fusion of the participating nuclei continues to emerge. One of the important aspects to this effect is the coupled channel formalism where the inelastic excitations to the collective multipole modes of vibration, rotation and a few nucleon transfer reactions are considered as doorways to fusion. This approach has been followed in numerous studies [4, 5] and found to explain sub-barrier enhancement of fusion excitation function and average angular momenta over those predicted by one-dimensional tunneling. While the rotational an vibrational coupling strengths can be calculated fairly accurately, it is difficult to calculate the transfer coupling strengths (*i.e.* form factors) except for a few nuclei near shell closure. However, aided by our knowledge of semiclassical theory [3], the form factors for the various transfer channels can be extracted from the experimental transfer probability data. In this presentation, one such experimental investigation in $^{32}S + ^{64}Ni$ and $^{28}Si + ^{68}Zn$

systems, where fusion data (*i.e.* cross sections and average angular momenta) exist [6,7], is reported.

^{32}S and ^{28}Si beams at 80–115 MeV bombarding energy from the 14UD BARC-TIFR Pelletron were used to study the direct reaction channels in ^{32}S + ^{64}Ni and ^{28}Si + ^{68}Zn systems with the help of a composite heavy ion gas detector system consisting of a position sensitive parallel grid avalanche counter and a Bragg curve spectroscopy detector. The detector system with angular acceptance of ~ 25° was placed at 45° or 75° downstream. Particle-γcoincidence, taken with two large area NaI(Tl) detectors, were used to (i) identify the neutron transfer channels which could not be done otherwise in the present set-up, and (ii) to extract the elastic events by subtracting the coincident yields of the inelastic and transfer channels. Performance of the gas detector system has been reported before [8] and details of the experimental set-up will be published elsewhere [9].

In the two sytems studied in this experiment, the one- and two-proton stripping (henceforth designated by $-1p$ and $-2p$) and one- and two-neutron pick-up ($+1n$ and $+2n$) channels were found to be the dominant channels. The proton pick-up, neutron stripping and multinucleon transfer channels were seen as weak channels mostly because of large negative Q-values for these channels. Although multinucleon transfer events were seen through the coincident gamma rays, their contribution to the associated dominant channels was found to be less than 15–20% in most cases. A detailed account of the contribution from the multinucleon transfer channels, as observed from the associated γ-ray intensities will be discussed in a forthcoming publication [10]. The transfer probabilities P_{tr}, defined as the ratio :

$$P_{tr}(r_0) = \frac{d\sigma_{tr} / d\Omega_{CM}}{d\sigma_{el} / d\Omega_{CM}}$$

were obtained from the experimentally determined cross sections for each distance of closest approach r_0 for the different transfer channels and at various bombarding energies in the two systems. The P_{tr} *vs* d_0 plots, where $d_0 = r_0 / (A_1^{1/3} + A_2^{1/3})$ (A_1 and A_2 being the masses of the interacting nuclei) are shown in Figure 1 for $-1p$ and $-2p$ channels in ^{28}Si + ^{68}Zn systems at various bombarding energies near the barrier. On the basis of the exponential radial dependence of the form factor : $F(r_0) = F(r_B) \exp[-\alpha(r_0 - r_B)]$, r_B being the barrier radius, the P_{tr} is expected to follow an exponential fall-off with r_0 as :

$$P_{tr}(r_0) = P_{tr}(r_B) \exp\left[-2\alpha(r_0 - r_B\right].$$

The quantity α is termed as the effective slope parameter. According to semiclassical theories, α is related to the binding energy E_B of the transferred particle of reduced mass μ in the target or the projectile nuclei, through the relation : $\alpha = \sqrt{2\mu E_B} / \hbar$. Thus, α is expected to be independent of the bombarding energy. The observed variation of α with bombarding energy in case of $-1p$ and $-2p$ transfer channels in ^{28}Si + ^{68}Zn, as can be seen in Figure 1, are plotted in Figure 2. A common feature for both the transfer channels that can be seen from the figure is that the dependence of α on energy is less prominent at the

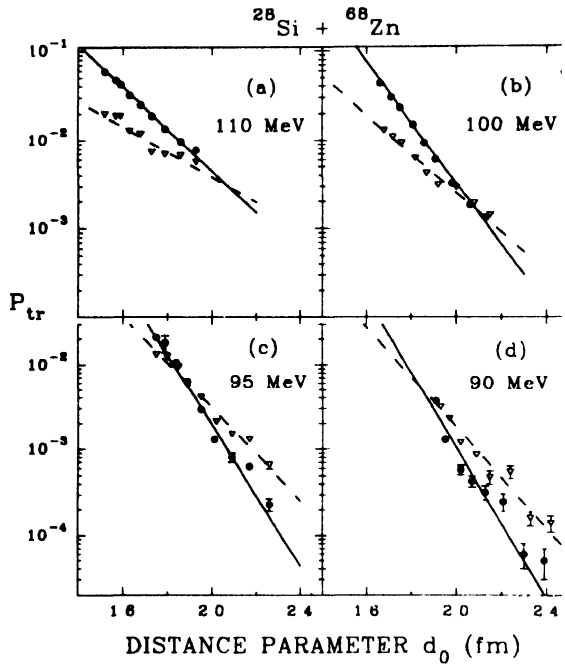

Figure 1. One- and two-proton transfer probabilities, plotted as function of distance parameter d_0 at various bombarding energies in $^{28}Si + ^{68}Zn$. The solid and the dashed lines are the fitted curves through $-1p$ (solid circles) and $-2p$ (hollow triangles) data points respectively

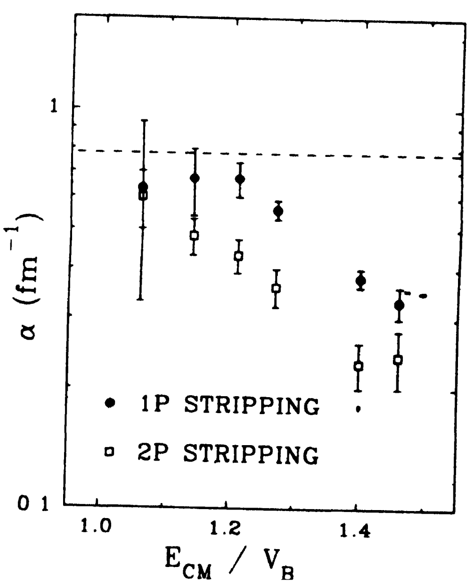

Figure 2. Effective Slope parameters α in one- and two-proton stripping, plotted as function of E_{CM}/V_B in $^{28}Si + ^{68}Zn$. The dashed and the dotted lines are the expected values of α_{1p} and α_{2p} from the semiclassical theory.

higher energies ($E_{CM}/V_B \gtrsim 1.3$, V_B being the barrier height) than at lower energies. In case of $-1p$ channel, α saturates at the value predicted by semiclassical theory at $E_{CM}/V_B \lesssim 1.25$. In case of the $-2p$ channel, however, α is approximately half the value predicted by semiclassical theory at $E_{CM} \sim V_B$. Such an anomalous behaviour of α indicates additional energy and angular momentum dependence of the form factor which cannot be taken into account by a semiclassical theory. This so-called 'slope anomaly' has been observed recently in two-neutron pick-up [11] and two-proton stripping [12] in $^{32,36}S + ^{92,98,100}Mo$ systems. The effect has been attributed by the authors to a diffractive process arising from the localization of form factors in the angular momentum space.

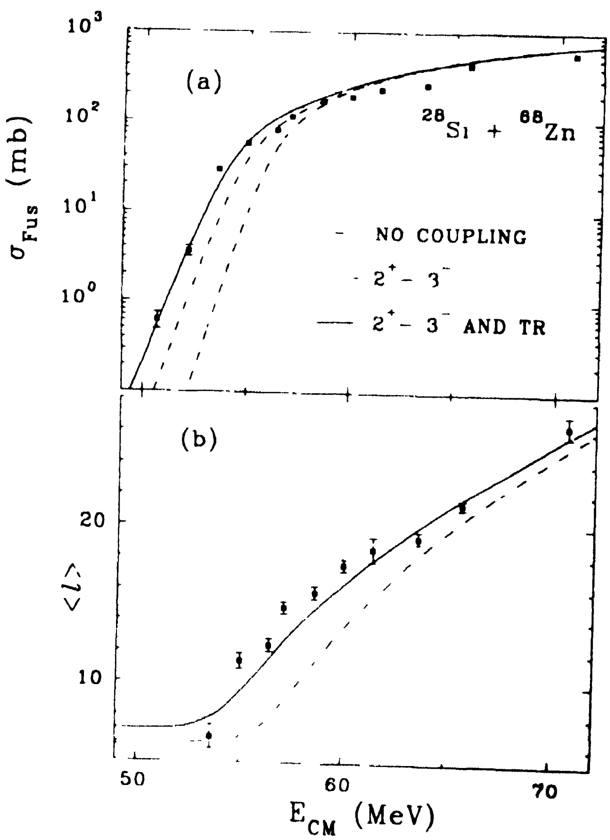

Figure 3. (a) Fusion cross sections and (b) average angular momenta, plotted as function of energy in $^{28}Si + ^{68}Zn$. Data points represented by solid squares are taken from ref. [7]. Results of coupled channel calculations including only the inelastic channels are shown by dot-dashed line in (a), and those including the inelastic and transfer channels by solid lines in (a) and (b).

Using the semiclassical approach of Broglia and Winther [3], the effective form factors F_0 per unit energy interval, at $r_0 = r_B$ were obtained directly from the transfer probability data for $-1p$ and $-2p$ channels. The values for $+1n$ channels were extracted from the γ-ray data and the spectroscopic strengths of the single particle states in the product nuclei, available from the existing light ion transfer reactions data. Details of the analysis procedure followed in extracting the form factors will be given elsewhere [10]. The form factors for the $+2n$ channels, also obtained from the γ-ray data, were not as reliable as in case of the $+1n$ channels because of non-availability of the relevant spectroscopic information.

The derived F_0 values were used as coupling strengths for the transfer channels, in addition to the 2^+, 3^- vibrational couplings, in the coupled channel code CCFUS [13]. Various excited states in the Q-value range of $Q_{gs} \lesssim Q \lesssim Q_{gs} - 4$ MeV were taken into account in the calculation [10]. The fusion cross sections and average angular momenta, calculated in this manner, are compared with the experimental data of ref. [7] in Figure 3 in case of $^{28}Si + ^{68}Zn$ system. Similar comparison is done for the other system *viz.* $^{32}S + ^{64}Ni$. Reasonable agreement found in both the systems between the calculated excitation functions including the transfer channels and the experimental data supports the fact that the transfer channels are equally important as the inelastic channels in explaining the subbarrier enhancement of fusion cross sections and average angular momenta in the coupled channel formalism.

In summary, the one- and two-nucleon transfer probabilities is $^{32}S + ^{64}Ni$ and $^{28}Si + ^{68}Zn$ reactions were measured at several energies near the barrier. The effective slope parameters for one- and two-proton stripping are seen to depend on energy, a behaviour not expected on the basis of semiclassical theory. The coupling strengths, extracted from the experimental data, were used in a simplified coupled channel calculation to obtain the fusion cross sections and average angular momenta. The calculated values including the transfer couplings are found to agree with the existing data reasonably well and hence supports the notion that the quasielastic channels act as doorways to fusion by lowering the effective barrier height and thus enhance the fusion cross section at sub-barrier energies.

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